

Masses and Residues of the Triply Heavy Spin-1/2 Baryons

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Abstract

We calculate the masses and residues of the triply heavy spin-1/2 baryons using the most general form of their interpolating current via QCD sum rules. We compare the obtained results with the existing theoretical predictions in the literature.

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1 Introduction

Recently, there have been significant experimental success on the identification and spectroscopy of the heavy baryons containing heavy bottom and charm quarks. By this time, all baryons containing a single charm quark predicted by the quark model have been observed. The heavy Λ_b , Σ_b , Ξ_b and Ω_b baryons with spin-1/2 together with the spin-3/2 Σ_b^* baryon containing a single bottom quark have also been discovered (for a review on the spectroscopy of the heavy flavor baryons at the Tevatron see for instance [1]). Recently, the CMS Collaboration at CERN reported the observation of the spin-3/2 heavy Ξ_b^* baryon [2]. Following these experimental success on the spectroscopy of the heavy baryons with a single heavy quark, the SELEX Collaboration announced their first observation of the doubly heavy spin-1/2 Ξ_{cc}^+ baryon with two charm quarks [3–5]. We hope that the LHCb detector at CERN will provide us with identification and detection of all doubly heavy and triply heavy baryons predicted by the quark model.

The experimental progresses on the spectroscopy of the heavy baryons have stimulated the theoretical works in this respect. There are many works on the spectroscopy of the heavy baryons with a single heavy quark in the literature. There are also dozen of works dedicated to the spectroscopy of the doubly heavy baryons, however, the number of works devoted to the investigation of the properties of the triply heavy baryons are relatively few. For some of the theoretical works dedicated to the spectroscopy of the triply heavy baryons with different approaches such as the effective field theory, the lattice QCD, the QCD bag model, different quark models, the variational approach, the hyper central model, the potential non-relativistic QCD and the Regge trajectory ansatz, see for instance [6–18]. The masses as well as the masses and residues of the triply heavy baryons for the Ioffe current are calculated within QCD sum rules in [19] and [20], respectively.

In the present work we extend our previous studies on the spectroscopy and mixing angles of the doubly heavy baryons [21–23] to the triply heavy baryons. We calculate the masses and residues of the triply heavy spin-1/2 baryons using the most general form of the interpolating current via QCD sum rules and compare the results with the predictions of the same approach in the case of Ioffe current [19, 20] as well as predictions of other theoretical approaches [6–18].

The layout of the article is as follows. In Section 2, we derive QCD sum rules for the masses and residues of the triply heavy spin-1/2 baryons. In Section 3, we numerically analyze the sum rules for the masses and residues and find the reliable working regions for the auxiliary parameters entered to the sum rules. We compare our numerical results with

Baryon	Q	Q'
Ω_{bbc}	b	c
Ω_{ccb}	c	b

Table 1: The quark contents of the triply heavy spin-1/2 baryons.

the predictions of the theoretical works existing in the literature and discuss the obtained results.

2 Masses and residues of the triply heavy spin-1/2 baryons

In order to obtain the QCD sum rules for the masses and residues of the triply heavy baryons we start considering the correlation function

$$\Pi(q) = i \int d^4x e^{iqx} \langle 0 | \mathcal{T} \{ \eta_{QQQ'}(x) \bar{\eta}_{QQQ'}(0) \} | 0 \rangle, \quad (2.1)$$

where $\eta_{QQQ'}$ is the interpolating current for these baryons and q is their four-momentum. The most general form of the interpolating current for the triply heavy spin-1/2 baryons can be written as

$$\eta_{QQQ'} = 2\epsilon_{ijk} \left\{ \left(Q^{iT} C Q'^j \right) \gamma_5 Q^k + \beta \left(Q^{iT} C \gamma_5 Q'^j \right) Q^k \right\}, \quad (2.2)$$

where i, j, k are the color indices, C is the charge conjugation operator and β is an arbitrary auxiliary parameter which we shall find its working region. The case $\beta = -1$ corresponds to the Ioffe current considered in [19, 20]. The heavy Q and Q' quarks for both members predicted by the quark model are given in Table 1. From this current one can formally obtain the interpolating current of the proton (neutron) by replacing $Q \rightarrow u$ and $Q' \rightarrow d$ ($Q \rightarrow d$ and $Q' \rightarrow u$).

The correlation function in Eq. (2.1) can be calculated in two different ways. In physical or phenomenological side it is calculated in terms of hadronic parts, while in QCD side it is evaluated in terms of quarks and gluons. The matching of these two representations then gives us the QCD sum rules for physical quantities under consideration. To suppress the contributions of the higher states and continuum we apply Borel transformation as well as continuum subtraction to both sides of the obtained sum rules.

In physical part, by saturating the correlation function with a complete set of hadronic states having the same quantum numbers as the interpolating current and by isolating the ground state baryons, we get

$$\Pi(q) = \frac{\langle 0 | \eta_{QQQ'}(0) | B(q) \rangle \langle B(q) | \bar{\eta}_{QQQ'}(0) | 0 \rangle}{q^2 - m_B^2} + \dots, \quad (2.3)$$

where dots stands for the contribution of the higher states and continuum. The matrix element of the interpolating current between the vacuum and the baryonic state is parameterized as

$$\langle 0 | \eta_{QQQ'}(0) | B(q, s) \rangle = \lambda_B u(q, s), \quad (2.4)$$

where λ_B is the residue of the heavy spin-1/2 baryons and $u(q, s)$ is their Dirac spinor. By performing summation over the spins of these baryons, we immediately obtain

$$\Pi(q) = \frac{\lambda_B^2 (\not{q} + m_B)}{q^2 - m_B^2} + \dots, \quad (2.5)$$

for the physical side, where we have only two independent Lorentz structures \not{q} and U to calculate the masses and residues.

In QCD side, the correlation function is calculated using the operator product expansion (OPE) in deep Euclidean region. By applying the Wick theorem and contracting out all quarks fields, we obtain the following expression in terms of the heavy quarks propagators:

$$\begin{aligned} \Pi(q) = & 4i\epsilon_{ijk}\epsilon_{lmn} \int d^4x e^{iqx} \langle 0 | \left\{ -\gamma_5 S_Q^{nj} S_{Q'}^{tmi} S_Q^{lk} \gamma_5 + \gamma_5 S_Q^{nk} \gamma_5 \text{Tr} [S_Q^{lj} S_{Q'}^{tmi}] \right. \\ & + \beta \left(-\gamma_5 S_Q^{nj} \gamma_5 S_{Q'}^{tmi} S_Q^{lk} - S_Q^{nj} S_{Q'}^{tmi} \gamma_5 S_Q^{lk} \gamma_5 + \gamma_5 S_Q^{nk} \text{Tr} [S_Q^{lj} \gamma_5 S_{Q'}^{tmi}] \right. \\ & \left. \left. + S_Q^{nk} \gamma_5 \text{Tr} [S_Q^{lj} S_{Q'}^{tmi} \gamma_5] \right) + \beta^2 \left(-S_Q^{nj} \gamma_5 S_{Q'}^{tmi} \gamma_5 S_Q^{lk} + S_Q^{nk} \text{Tr} [S_{Q'}^{mi} \gamma_5 S_Q^{lj} \gamma_5] \right) \right\} | 0 \rangle, \end{aligned} \quad (2.6)$$

where $S' = CS^T C$.

To proceed in QCD side, we write the coefficients of the selected structures as the dispersion integral

$$\Pi_i(q) = \int \frac{\rho_i(s)}{s - q^2} ds, \quad (2.7)$$

where $\rho_i(s)$ are the spectral densities and they are found from the imaginary parts of the $\Pi_i(q)$ functions. Here $i = 1$ and 2 correspond to the structures \not{q} and U , respectively. Our

main task in the following is to calculate these spectral densities. To go further, we need the explicit expression of the heavy quark propagator. It is given as

$$\begin{aligned}
S_Q(x) &= \frac{m_Q^2}{4\pi^2} \frac{K_1(m_Q\sqrt{-x^2})}{\sqrt{-x^2}} - i \frac{m_Q^2 \not{x}}{4\pi^2 x^2} K_2(m_Q\sqrt{-x^2}) \\
&- ig_s \int \frac{d^4 k}{(2\pi)^4} e^{-ikx} \int_0^1 du \left[\frac{\not{k} + m_Q}{2(m_Q^2 - k^2)^2} G^{\mu\nu}(ux) \sigma_{\mu\nu} + \frac{u}{m_Q^2 - k^2} x_\mu G^{\mu\nu} \gamma_\nu \right] + \dots,
\end{aligned} \tag{2.8}$$

where K_1 and K_2 are the modified Bessel function of the second kind. Using this propagator in Eq. (2.6) and after performing lengthy calculations we obtain the spectral densities

$$\begin{aligned}
\rho_1(s) &= \frac{1}{64\pi^4} \int_{\psi_{min}}^{\psi_{max}} \int_{\eta_{min}}^{\eta_{max}} d\psi d\eta \left\{ -3\mu_{QQQ'} \left[-12(-1+\eta)m_Q m_{Q'}(-1+\beta)^2 \right. \right. \\
&+ \psi^2 \eta (3\mu_{QQQ'} - 2s) [5 + \beta(2+5\beta)] + \psi \left(2m_Q^2(-1+\beta)^2 - 12m_Q m_{Q'}(-1+\beta^2) \right. \\
&+ \left. \left. (-1+\eta)\eta(3\mu_{QQQ'} - 2s) [5 + \beta(2+5\beta)] \right) \right] \Bigg\} \\
&+ \frac{\langle g_s^2 GG \rangle}{256\pi^4 m_Q m_{Q'}} \int_{\psi_{min}}^{\psi_{max}} \int_{\eta_{min}}^{\eta_{max}} d\psi d\eta \left\{ 6(-3+4\psi)(-1+\psi+\eta)m_Q^2(-1+\beta^2) \right. \\
&+ 6(-3+4\eta)(-1+\psi+\eta)m_{Q'}^2(-1+\beta^2) + m_Q m_{Q'} \left[48\psi^2(1+\beta^2) + \psi[-63 \right. \\
&+ 68\eta - 30\beta + 8\eta\beta + (-63+68\eta)\beta^2] + 2(-1+\eta) \left(-3[3+\beta(2+3\beta)] \right. \\
&+ \left. \left. 2\eta[5+\beta(2+5\beta)] \right) \right] \Bigg\},
\end{aligned} \tag{2.9}$$

and

$$\begin{aligned}
\rho_2(s) = & \frac{1}{32\pi^4} \int_{\psi_{min}}^{\psi_{max}} \int_{\eta_{min}}^{\eta_{max}} d\psi d\eta \left\{ 3\mu_{QQQ'} \left[\eta(-1 + \psi + \eta)m_{Q'}(\mu_{QQQ'} - s)(-1 + \beta)^2 \right. \right. \\
& + 6\psi(-1 + \psi + \eta)m_Q(\mu_{QQQ'} - s)(-1 + \beta^2) + m_Q^2 m_{Q'} [5 + \beta(2 + 5\beta)] \left. \right] \Bigg\} \\
& + \frac{\langle g_s^2 GG \rangle}{128\pi^4 m_Q m_{Q'}} \int_{\psi_{min}}^{\psi_{max}} \int_{\eta_{min}}^{\eta_{max}} \frac{d\psi d\eta}{\psi\eta} \left\{ -2(-1 + \eta)\eta m_Q m_{Q'}^2 (-1 + \beta)^2 \right. \\
& - 2\psi^3 \eta(-1 + \beta) \left[-9m_{Q'}(\mu_{QQQ'} - s)(1 + \beta) + \eta(2\mu_{QQQ'} - 3s) \left(m_Q(-1 + \beta) \right. \right. \\
& + 6m_{Q'}(1 + \beta) \left. \right) \left. \right] + \psi m_Q \left(3\eta^3(\mu_{QQQ'} - s)(-1 + \beta)^2 + 2m_Q m_{Q'}(-1 + \beta^2) \right. \\
& + 3\eta^2 \left[-[(\mu_{QQQ'} - s)(-1 + \beta)^2] + 2m_Q m_{Q'}(-1 + \beta^2) + 4m_{Q'}^2(1 + \beta^2) \right] \\
& + \eta \left[-5m_{Q'}^2(-1 + \beta)^2 - 2m_Q m_{Q'}(-1 + \beta^2) + m_Q^2 [5 + \beta(2 + 5\beta)] \right] \Bigg\} \\
& + \psi^2 \left(-4m_Q^2 m_{Q'}(-1 + \beta^2) + \eta^2(7\mu_{QQQ'} - 9s)(-1 + \beta) \left[m_Q(-1 + \beta) + 6m_{Q'}(1 + \beta) \right] \right. \\
& - 2\eta^3(2\mu_{QQQ'} - 3s)(-1 + \beta) \left[m_Q(-1 + \beta) + 6m_{Q'}(1 + \beta) \right] + \eta \left[-18m_{Q'}(\mu_{QQQ'} - s) \right. \\
& \times (-1 + \beta^2) + 12m_Q m_{Q'}^2(1 + \beta^2) - m_Q^3 [5 + \beta(2 + 5\beta)] \left. \right] \Bigg\}, \tag{2.10}
\end{aligned}$$

where,

$$\begin{aligned}
\mu_{QQQ'} &= \frac{m_Q^2}{1 - \psi - \eta} + \frac{m_Q^2}{\eta} + \frac{m_{Q'}^2}{\psi} - s, \\
\eta_{min} &= \frac{1}{2} \left[1 - \psi - \sqrt{(1 - \psi) \left[1 - \psi - \frac{4\psi m_Q^2}{\psi s - m_{Q'}^2} \right]} \right], \\
\eta_{max} &= \frac{1}{2} \left[1 - \psi + \sqrt{(1 - \psi) \left[1 - \psi - \frac{4\psi m_Q^2}{\psi s - m_{Q'}^2} \right]} \right], \\
\psi_{min} &= \frac{1}{2s} \left[s + m_{Q'}^2 - 4m_Q^2 - \sqrt{(s + m_{Q'}^2 - 4m_Q^2)^2 - 4m_{Q'}^2 s} \right], \\
\psi_{max} &= \frac{1}{2s} \left[s + m_{Q'}^2 - 4m_Q^2 + \sqrt{(s + m_{Q'}^2 - 4m_Q^2)^2 - 4m_{Q'}^2 s} \right]. \tag{2.11}
\end{aligned}$$

Now we match the two sides of the correlation function for each structure to get the QCD sum rules for the masses and residues of the triply heavy baryons. After applying

the Borel transformation and continuum subtraction to suppress the contributions coming from the higher states and continuum, we get

$$\begin{aligned}\lambda_B^2 e^{\frac{-m_B^2}{M^2}} &= \int_{(2m_Q+m_{Q'})^2}^{s_0} ds \rho_1(s) e^{\frac{-s}{M^2}}, \\ \lambda_B^2 m_B e^{\frac{-m_B^2}{M^2}} &= \int_{(2m_Q+m_{Q'})^2}^{s_0} ds \rho_2(s) e^{\frac{-s}{M^2}},\end{aligned}\quad (2.12)$$

where M^2 and s_0 are Borel mass parameter and continuum threshold, respectively. By eliminating the residues from the above equations, we can calculate the masses from either

$$m_B^2 = \frac{\int_{(2m_Q+m_{Q'})^2}^{s_0} ds \, s \rho_i(s) e^{\frac{-s}{M^2}}}{\int_{(2m_Q+m_{Q'})^2}^{s_0} ds \, \rho_i(s) e^{\frac{-s}{M^2}}}, \quad i = 1 \text{ or } 2, \quad (2.13)$$

or

$$m_B = \frac{\int_{(2m_Q+m_{Q'})^2}^{s_0} ds \rho_2(s) e^{\frac{-s}{M^2}}}{\int_{(2m_Q+m_{Q'})^2}^{s_0} ds \rho_1(s) e^{\frac{-s}{M^2}}}. \quad (2.14)$$

3 Numerical results

Now we are ready to numerically analyze the obtained sum rules in the previous section and calculate the numerical values of the masses and residues of the triply spin-1/2 heavy baryons. For this aim we take the quark masses as both their pole values $m_b = (4.8 \pm 0.1) \text{ GeV}$ and $m_c = (1.46 \pm 0.05) \text{ GeV}$ [24] as well as their \overline{MS} values $\bar{m}_b(\bar{m}_b) = (4.16 \pm 0.03) \text{ GeV}$, $\bar{m}_c(\bar{m}_c) = (1.28 \pm 0.03) \text{ GeV}$ [25]. For the numerical value of the gluon condensate we use $\langle g_s^2 GG \rangle = 4\pi^2(0.012 \pm 0.004) \text{ GeV}^4$ [24].

The sum rules obtained in the previous section incorporate also three auxiliary parameters which we find their working regions in the following. These parameters are the Borel mass parameter M^2 , the continuum threshold s_0 and the general parameter β enrolled to the general current of the baryons under consideration. The working regions of these parameters are found such that the variations of the masses and residues are very weak with respect to them.

The continuum threshold s_0 is not completely capricious but it is related to the energy of the first excited state. We have not adequate knowledge about the first excited states of the baryons under consideration, but our analysis show that when we choose the continuum threshold in the intervals $s_0 = (140 - 148) \text{ GeV}^2$ and $s_0 = (74 - 81) \text{ GeV}^2$ respectively for the Ω_{bbc} and Ω_{ccb} baryons in the case of pole quark masses, the results very weakly depend

on s_0 . In the case of \overline{MS} values of the quark masses, the working regions for the continuum threshold are obtained as $s_0 = (117 - 125) \text{ GeV}^2$ and $s_0 = (64 - 70) \text{ GeV}^2$ for the baryons Ω_{bbc} and Ω_{ccb} , respectively.

Now we proceed to find the working region for the Borel mass parameter M^2 . The upper bound on this parameter is found demanding that the pole contribution is high compared to the contributions of the continuum and higher states. This means that the relation,

$$\frac{\int_{(2m_Q+m_{Q'})^2}^{s_0} \rho(s) e^{-s/M^2}}{\int_{(2m_Q+m_{Q'})^2}^{\infty} \rho(s) e^{-s/M^2}} \Bigg\rangle 1/2, \quad (3.15)$$

is satisfied. This condition leads to the following upper values for M^2 :

$$M_{max}^2 = \begin{cases} 22 \text{ GeV}^2, & \text{for } \Omega_{bbc} \\ 18 \text{ GeV}^2, & \text{for } \Omega_{ccb}. \end{cases} \quad (3.16)$$

The lower bound on M^2 is calculated requiring that the contribution of the perturbative part exceeds the nonperturbative contributions. From this restriction we obtain

$$M_{min}^2 = \begin{cases} 12 \text{ GeV}^2, & \text{for } \Omega_{bbc} \\ 9 \text{ GeV}^2, & \text{for } \Omega_{ccb}. \end{cases} \quad (3.17)$$

Our final task is to determine the working region for the auxiliary parameter β . Instead of discussing the variations of the physical observables with respect to this parameter in the interval $(-\infty, +\infty)$, we define $\beta = \tan\theta$ and look for the variations with respect to $\cos\theta$ in the interval $[-1, 1]$. Our numerical results show that in the domains $[-0.5, -0.9]$ and $[0.5, 0.9]$, the residues depend weakly on $\cos\theta$. Here we should mention that the Ioffe current corresponds to $\cos\theta = -0.71$ and lies inside the reliable region. Note also that as the mass sum rule is the ratio of two expressions including β in Eq. (2.13), the masses show a very good stability with respect to $\cos\theta$ in the whole allowed region.

Considering the working regions of the auxiliary parameters we obtain the numerical values for the masses and residues of the triply heavy spin-1/2 baryons as presented in Tables 2 and 3 for both structures. For comparison we also present the numerical predictions of other theoretical approaches such as the modified bag model [12], the relativistic three-quark model [13], the non-relativistic three-quark model [14] and QCD sum rules but Ioffe current [19, 20]. As far as the masses are considered, our central value results are slightly higher than the other predictions. The closest results to our predictions are the results of

	This work (\not{q})	This work (U)	[20]	[12]	[13]	[19]	[14]
Ω_{bbc}	11.73 ± 0.16	11.71 ± 0.16	11.50 ± 0.11	11.139	11.280	10.30 ± 0.10	11.535
Ω_{ccb}	8.50 ± 0.12	8.48 ± 0.12	8.23 ± 0.13	7.984	8.018	7.41 ± 0.13	8.245
$\overline{\Omega}_{bbc}$	10.59 ± 0.14	10.56 ± 0.14	10.47 ± 0.12	-	-	-	-
$\overline{\Omega}_{ccb}$	7.79 ± 0.11	7.74 ± 0.11	7.61 ± 0.13	-	-	-	-

Table 2: The masses of the triply heavy spin-1/2 baryons in the units of GeV compared with other theoretical predictions. For the baryons with over-line, the \overline{MS} values of the quark masses have been used.

	This work (\not{q})	This work (U)	[20]
Ω_{bbc}	0.53 ± 0.17	0.45 ± 0.15	0.68 ± 0.15
Ω_{ccb}	0.38 ± 0.13	0.30 ± 0.10	0.47 ± 0.10
$\overline{\Omega}_{bbc}$	0.85 ± 0.28	0.65 ± 0.22	0.68 ± 0.15
$\overline{\Omega}_{ccb}$	0.56 ± 0.18	0.38 ± 0.13	0.47 ± 0.10

Table 3: The residues of the triply heavy spin-1/2 baryons in the units of GeV^3 compared with the existing theoretical prediction for Ioffe current. For the baryons with over-line, the \overline{MS} values of the quark masses have been used.

the non-relativistic three-quark model [14] and QCD sum rules with the Ioffe current [20], respectively. The lower predictions for the masses belong, respectively, to QCD sum rules with the Ioffe current [19] and the modified bag model [12]. From Table 2 we see that the two structures in our case give approximately the same results. This Table also shows that the results depend on the quarks masses considerably and change (9-10)% when going from the pole masses to the \overline{MS} scheme masses. Here, we should mention that considering Eq. (2.14) does not affect considerably the results of masses presented in Table 2.

In the case of the residues, against the [20] our results depend on the quark masses such that when going from the pole to the \overline{MS} the results change (21-37)%. This is an expected results that the residues depend more on quark masses in comparison with the baryon masses. From Table 3 it is also clear that the results depend on the choice of the structure. The structure U give the results (15-30)% lower than those of the structure \not{q} . In the case of the pole masses of the quarks, our predictions on the residues are considerably small in comparison with those of the [20]. The maximum difference between two works belongs to the Ω_{ccb} baryon and U structure which is approximately 36%. For the residues

in \overline{MS} scheme, our result is very close to that of the [20] for the structure U and $\overline{\Omega}_{bbc}$, while the maximum difference with 23% between predictions of two studies belongs to the $\overline{\Omega}_{ccb}$ baryon and also the structure U .

In conclusion, we have calculated the masses and residues of the triply heavy spin-1/2 baryons using the most general form of their interpolating current in the framework of QCD sum rules. We found the reliable working regions for each of the auxiliary parameters entered the calculations. Our results on the masses are slightly higher than the previous predictions like the modified bag model, different relativistic and non-relativistic quark models as well as QCD sum rules for the Ioffe current. We obtained residues considerably different than the existing predictions via QCD sum rules with Ioffe current. We hope that the LHC at CERN will provide opportunity to experimental studying of these baryons in near future.

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